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# Processing of Hybrid Structures Consisting of Al-Based Metal Matrix Composites (MMCs) With Metallic Reinforcement of Steel or Titanium

**by Michael Aghajanian, Eric Klier, Kevin Doherty, Brian Givens, Matthew Watkins, Allyn McCormick, and Prashant Karandikar**

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**A reprint from the *Minerals, Metals & Materials Society Annual Meeting Supplemental Proceedings*, pp. 629–638, San Antonio, TX, 3–7 March 2013.**

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Particulate-reinforced, aluminum (Al)-based metal matrix composites (MMCs) offer many advantages as engineering materials, including low density relative to titanium- and steel-based metals, high specific stiffness, high specific strength, tailorable coefficient of thermal expansion (CTE), and high wear resistance. However, these materials have low toughness and elongation relative to pure structural metals due to the presence of the brittle ceramic particles within the aluminum matrix. The present work aims to resolve the low elongation weakness of Al-based MMCs by incorporating metallic "macro-reinforcement" into the material, forming a hybrid structure. Example hybrid configurations are Al-based MMCs with an internal network of steel or titanium rebar, or Al-based MMCs cast into a steel or titanium grid structure. With proper selection of the MMC formulation, its CTE can be matched to that of the metallic macro-reinforcement, leading to a stress-free structure. Alternatively, the CTEs can be tailored such that the metallic macro-reinforcement applies a compressive residual stress to the MMC, thus providing enhanced mechanical response. Specifically, the work describes processing of MMC-metal hybrid structures, examines interfacial microstructures, and assesses failure behavior.

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# PROCESSING OF HYBRID STRUCTURES CONSISTING OF Al-BASED METAL MATRIX COMPOSITES (MMCs) WITH METALLIC REINFORCEMENT OF STEEL OR TITANIUM

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Keywords: Metal Matrix Composites, Microstructures, Metal Casting, Hybrid Structures

## Abstract

Particulate reinforced, Al-based metal matrix composites (MMCs) offer many advantages as engineering materials, including low density relative to titanium and steel- based metals, high specific stiffness, high specific strength, tailorable coefficient of thermal expansion (CTE), and high wear resistance. However, these materials have low toughness and elongation relative to pure structural metals due to the presence of the brittle ceramic particles within the aluminum matrix. The present work aims to resolve the low elongation weakness of Al-based MMCs by incorporating metallic "macro-reinforcement" into the material, forming a hybrid structure. Example hybrid configurations are Al-based MMCs with an internal network of steel or titanium rebar, or Al-based MMCs cast into a steel or titanium grid structure. With proper selection of the MMC formulation, its CTE can be matched to that of the metallic macro-reinforcement, leading to a stress-free structure. Alternatively, the CTEs can be tailored such that the metallic macro-reinforcement applies a compressive residual stress to the MMC, thus providing enhanced mechanical response. Specifically, the work describes processing of MMC-metal hybrid structures, examines interfacial microstructures, and assesses failure behavior.

## Introduction

Discontinuously reinforced MMCs are of interest due to their improved mechanical and thermal properties relative to unreinforced alloys. Discontinuous reinforcement provides isotropic properties as compared to that of continuous-fiber-reinforced composites. Moreover, these materials are versatile and can be tailored for specific uses by altering processing conditions and/or raw materials. For instance, factors such as the alloy chemistry, the reinforcement shape (particulate, platelet, whisker, chopped fiber etc.), the reinforcement chemistry ($Al_2O_3$, SiC, etc.), the reinforcement loading, the processing method, post heat treatment, and cold work can have a significant impact on the structural behavior of the resultant composite. Such composites are now seeing widespread use in thermal management, precision equipment, and automotive applications where composition and microstructure are tailored to provide the desired mechanical and/or thermal properties [1-3]. However, broader use of these materials is being limited by a lack of ductility, with particulate reinforced MMCs tending to have elongations an order of magnitude below those of the unreinforced base alloy.

Structural metals formed into hollow, periodic cellular structures are of interest due to their very high stiffness to weight ratio and high damage tolerance (e.g., very high compressibility and

elongation). Example cellular configurations are sandwich structures with honeycomb, corrugated, foam, and lattice truss cores. Key applications include high specific stiffness panels and beams, fluid flow structures, thermal management substrates, and blast wave mitigation panels [4]. Issues with these structures are anisotropy and susceptibility to buckling failure.

The present work examines hybrid structures where MMC is formed inside a metallic cellular structure, with the goal of combining the advantageous properties of both individual materials. In particular, the aim is to maintain the high specific stiffness of MMC, but use the hybrid metallic reinforcement to overcome the major downside of low elongation. Key issues to address are MMC to metal interface, CTE mismatch stress, and component design, which will be discussed herein.

## MMC Materials Processing and Thermal Properties

The present work focused on particulate reinforced Al/SiC and $Al/Al_2O_3$ MMCs. The advantages of $Al_2O_3$ particles, as opposed to SiC, are lower cost, greater availability, and non-reactivity with Al. The lack of reactivity with Al provides broad freedom with respect to alloy selection. The advantages of SiC particles are lower density, higher hardness, higher stiffness, and greater thermal stability (high thermal conductivity and low thermal expansion). The composites were produced using a casting process [5, 6], where ceramic powders were pre-wet with Al alloy using a pressureless infiltration technique, dispersed to a particle loading that provided fluidity, and then gravity cast using traditional means (Figure 1). Ceramic particle size and alloy composition were controlled by raw material selection, and particle loading was controlled by the dispersion process. In the situation where desired particle loadings were above the fluidity limit of the melt, the higher particle packing was achieved through sedimentation of the particles post casting. Example Al/SiC and $Al/Al_2O_3$ microstructures are provided in Figure 2.

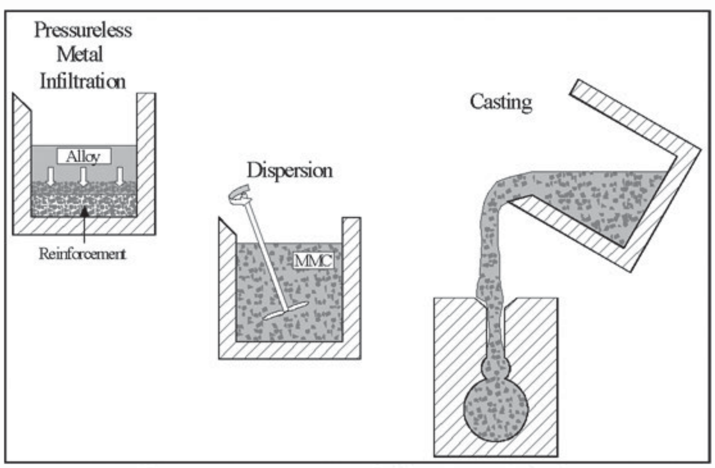


Figure 1. Process Schematic for MMC Fabrication

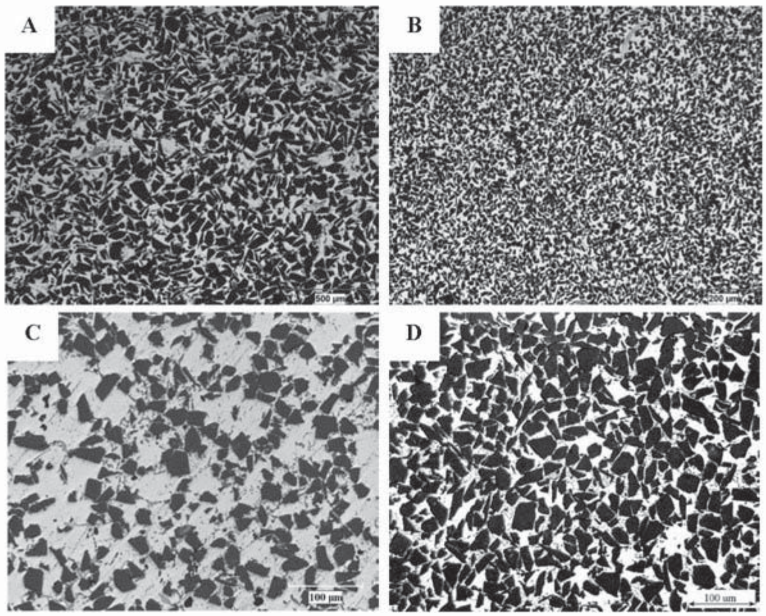


Figure 2. Example MMC Microstructures (optical photomicrographs)
A: 58 μm $Al_2O_3$ particles, 43% loaded
B: 12 μm $Al_2O_3$ particles, 32% loaded
C: 12 μm SiC particles, 30% loaded
D: 29 μm SiC particles, 55% loaded

The coefficient of thermal expansion (CTE) of MMCs is strongly dependent on the particle chemistry and loading. Understanding the effect of these variables on CTE is required for the production of hybrid MMC/Metal structures, as this allows stress free (CTE matched) assemblies to be fabricated. Or, it allows structures with desired residual stress levels to be produced (e.g., pre-loading the more brittle MMC phase in compression). Figure 3 provides a plot of MMC CTEs as a function of particle chemistry and loading, and also provides comparison to structural metals [7]. The MMC CTEs were measured by the thermomechanical analysis (TMA) method per ASTM 831. As best as possible, all data are from the 20 to 500°C temperature range.

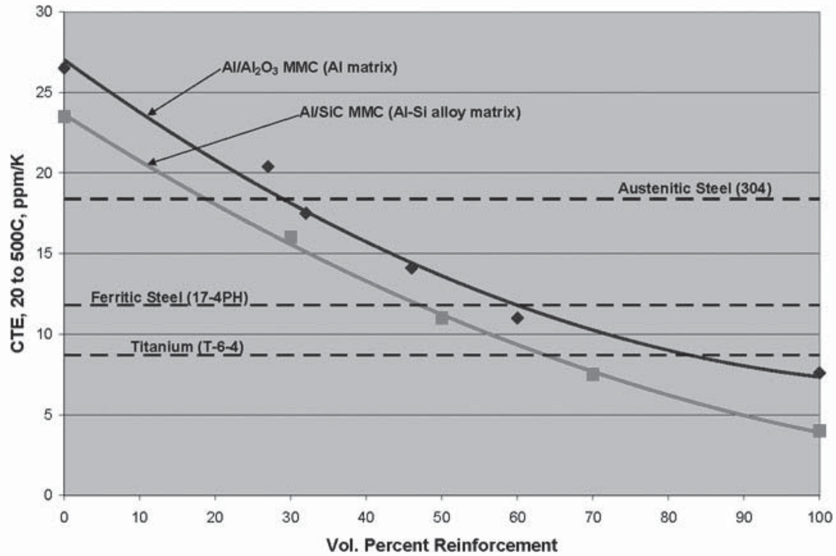


Figure 3. CTEs of Al/$Al_2O_3$ and Al/SiC MMCs vs. Reinforcement Content, with Comparison to Structural Metals

### Fabrication of and Testing Metal Hybrid Structures

Various types of hybrid structures were produced by simply casting MMC into hollow and/or cellular metallic structures. Unlike traditional casting, however, a residence time was used where the MMC slurry was maintained in the molten state while in contact with the structural metallic element. This residence time allowed an interface to be formed between the two materials. A typical residence time was 1.5 hours. Examples of high specific stiffness panel geometries are provided in Figure 4, and beam structures are shown in Figure 5.

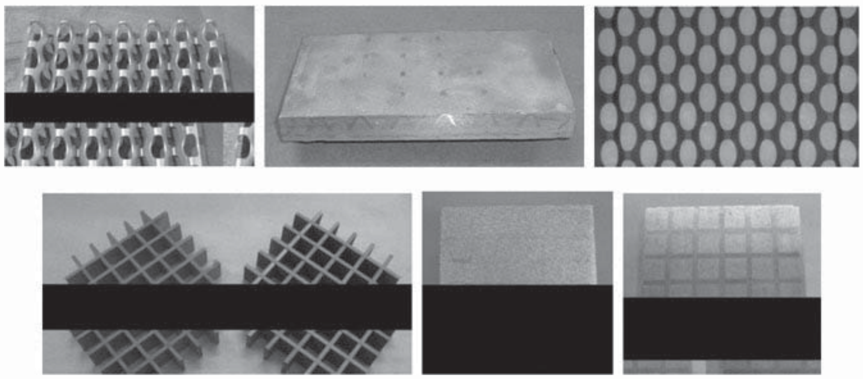

Figure 4. High Specific Stiffness and Damage Tolerant MMC/Metal Hybrid Panel Structures
TOP ROW: Corrugated/Perforated Steel Sheet, Encapsulated in $Al/Al_2O_3$ MMC, X-ray Image
BOTTOM ROW: Ti Strip-Slotted Grids, Encapsulated in $Al/Al_2O_3$ MMC, Ground

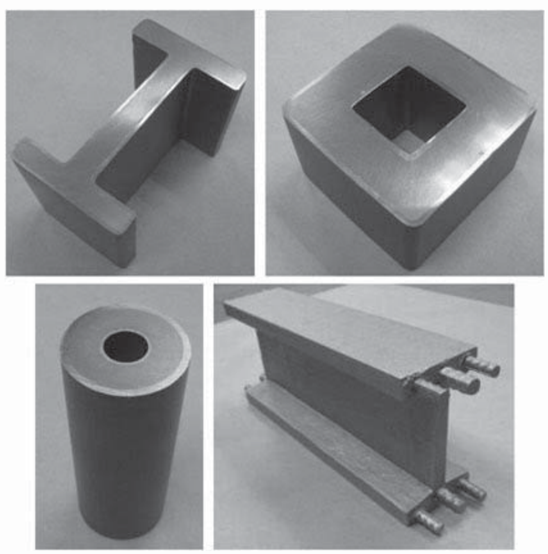

Figure 5. High Specific Stiffness MMC/Metal Hybrid Beams with Resistance to Catastrophic Failure ("exoskeleton" approach with steel skin and MMC core; and "bone" approach with rebar-like reinforcement in MMC)

Results showing elastic-plastic failure of a MMC/Steel hybrid beam are provided in Figure 6, together with a comparison to the predicted failure by finite element modeling (the modeling used 10-node tetragonal solid elements with mesh optimization to provide accurate non-linear, post-yield analysis). The beam consisted of a 100 mm x 100 mm x 3 mm thick austenitic steel box beam with a 6 mm thick internal skin of Al/SiC-55p MMC (i.e., total wall thickness of 9 mm). A 100% steel beam of the same mass would have a wall thickness of only 5.5 mm, making it much more susceptible to buckling failure. Moreover, with both the MMC and steel having the same Young's modulus of 200 GPa, the thicker hybrid beam is 59 percent stiffer than an equal mass 100% steel beam. Finally, the presence of the steel skin prevented brittle failure of the beam, as would be typical for a beam constructed of 100% cast MMC. Instead, a ductile failure mode is observed. Aiding this behavior was the use of an austenitic steel skin (rather than ferritic steel). As shown in Figure 3, austenitic steel has much higher CTE than Al/SiC-55p MMC. Thus, upon cooling from processing temperature, the steel pre-compresses the MMC, which allows greater load to be applied to the beam before a critical tensile stress is reached in the MMC phase.

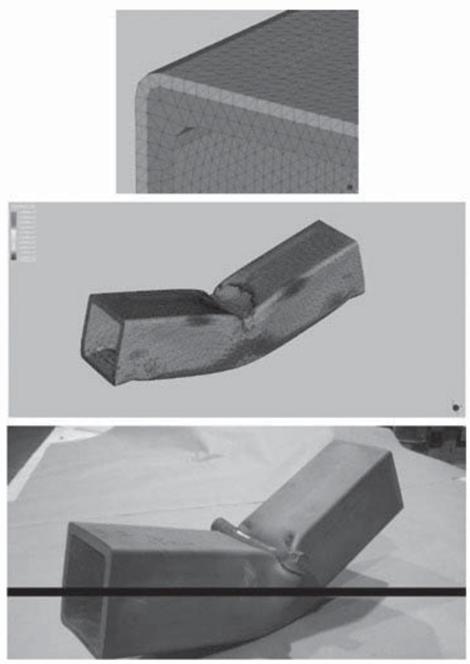

Figure 6. Finite Element Analysis Result for Macro-Composite Box Beam (thick austenitic steel skin with Al/SiC MMC core)
TOP: Computer Model with Tetragonal Mesh Elements
MIDDLE: Finite Element Result with Non-Linear Elastic-Plastic Behavior at High Strain
BOTTOM: Actual Testing Result, Matching Modeling

## Interfaces in MMC/Metal Hybrid Structures

MMC/Metal hybrid structures were produced in a systematic fashion to evaluate the interface formation between the two phases. Variables studied were the type of metal (steel and titanium), the process temperature, and the residence time of the molten MMC in contact with the structural metal. Typical results for the microstructure and chemistry of the interface region are provided in Figure 7 and Table I (MMC/Steel system) and in Figure 8 and Table II (MMC/Ti system). In both systems, an Al-based intermetallic region exists between the MMC and metal, with the Al content decreasing across the interface towards the metal reinforcing element.

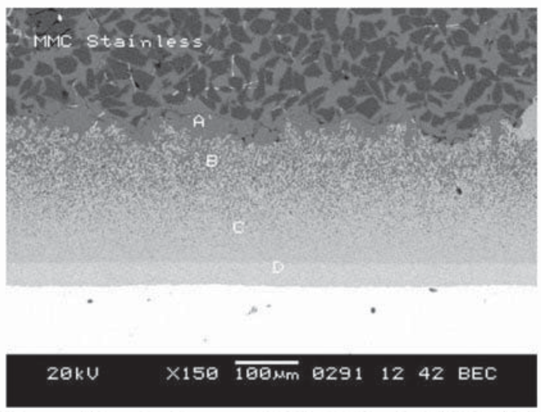


Figure 7. SEM Image of Interface between 304 SS Grid and $Al/Al_2O_3$ MMC Encapsulant

Table I. EDAX Results for 304 SS – $Al/Al_2O_3$ MMC System (in atomic %)

| | Area A | Area B | Area C | Area D |
|---|---|---|---|---|
| Al | 96.2 | 86.6 | 75.9 | 67.3 |
| Fe | --- | 10.2 | 20.1 | 23.3 |
| Cr | 0.5 | 1.0 | 2.2 | 6.8 |
| Ni | --- | --- | 0.7 | 2.6 |
| Mg | 3.3 | 2.2 | --- | --- |
| Si | --- | --- | 1.2 | --- |

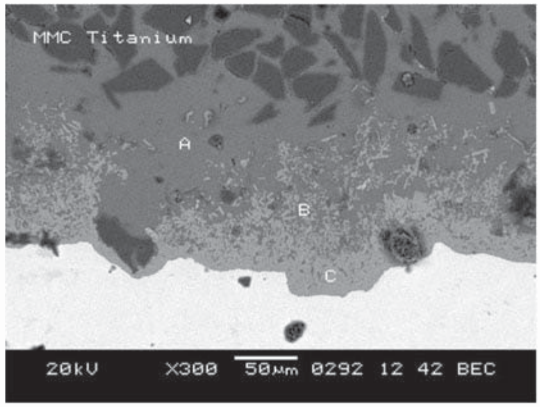


Figure 8. SEM Image of Interface between CP Ti Grid and $Al/Al_2O_3$ MMC Encapsulant

Table II. EDAX Results for CP Ti – $Al/Al_2O_3$ MMC System (in atomic %)

| | Area A | Area B | Area C |
|---|---|---|---|
| Al | 97.5 | 80.4 | 69.9 |
| Ti | --- | 16.4 | 26.7 |
| Mg | 2.5 | 1.4 | --- |
| Si | --- | 1.9 | 3.4 |

Both of the samples shown in Figures 7 and 8 were processed with an $Al/Al_2O_3$-50p MMC that had an Al-4Mg matrix alloy. The processing time and temperature were chosen in both cases to yield a reaction zone in the 100 to 200 µm range for analysis. The morphology of the interface region was very different in both cases, showing uniform dissolution of the steel, and very non-uniform dissolution of the Ti.

To assess the effect of processing conditions on the thickness of interface region formation in the MMC/Steel and MMC/Ti systems, Figure 9 plots reaction zone thickness vs. a broad residence time at 750°C. The results indicate that the reaction zone forms faster in the Ti system (because of the non-uniform layer formation in the Ti system (Figure 8), the reported thickness is an average of 6 random measurement locations). Across the time studied, the zone formation in the steel system is near linear.

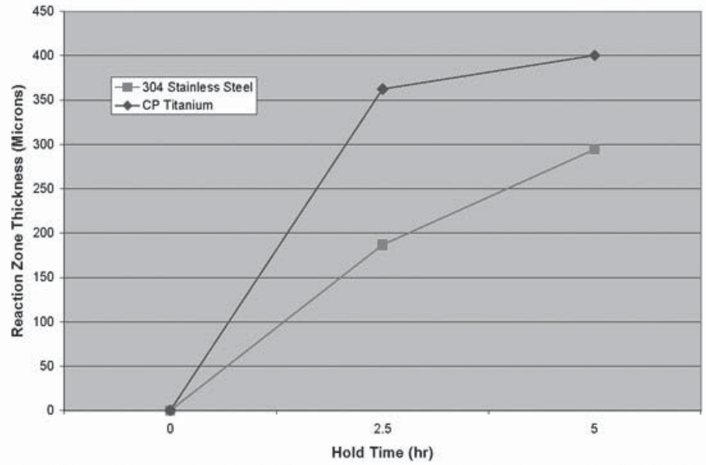


Figure 9. Effect of Processing Condition on Formation of Interface Region in MMC/Steel and MMC/Ti Hybrid Structures ($Al/Al_2O_3$ system with Al-4Mg matrix alloy)

## Summary

An evaluation of hybrid structures consisting of MMC reinforced with a structural metal (steel or Ti) was conducted, with the goal of maintaining the advantageous properties of MMCs (e.g., very high specific stiffness) while overcoming the weakness of low elongation. Key findings were:

- A wide range of hybrid structure geometries can be fabricated by casting MMC into a hollow structural metallic component
- Material formulations can be selected to yield stress-free hybrid bodies (i.e., matched CTE systems), or bodies with desired press-stressed conditions (i.e., loading MMC phase in compression)
- Ductile failure of hybrid structures can be achieved, despite presence of low elongation MMC phase
- MMC to metal interfaces consist of intermetallic phases, with thickness of region controlled by metal type (e.g., steel or Ti) and processing conditions

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